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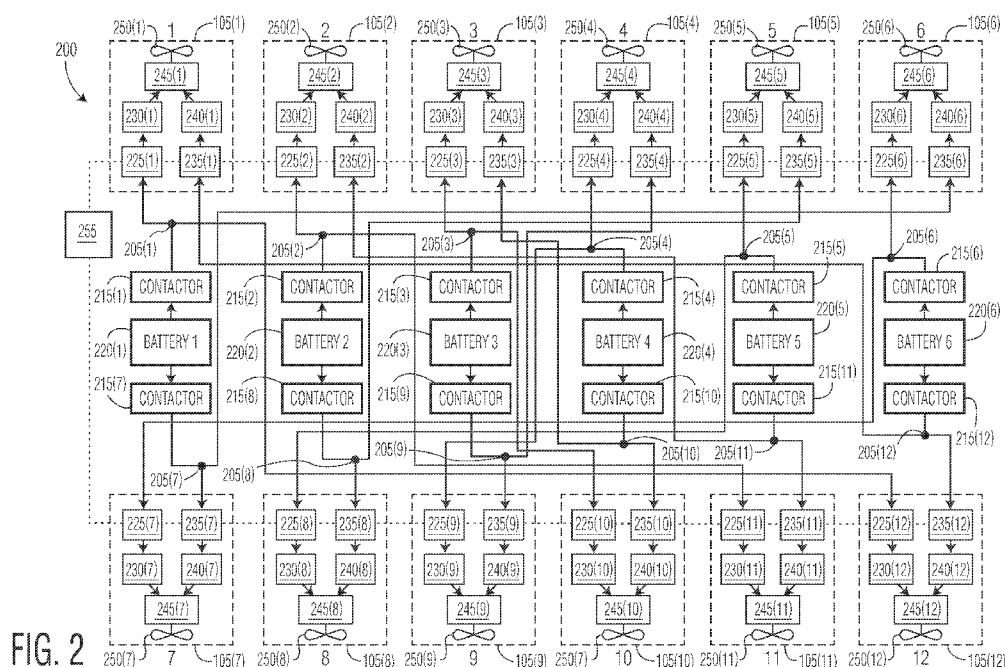
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(54) Title: ELECTRICALLY POWERED PROPULSION SYSTEMS FOR AIRCRAFT



(57) Abstract: An electrically powered propulsion system for an aircraft includes batteries, electric propulsion assemblies, and power distribution circuits. Each battery is coupled with two or more of the electric propulsion assemblies via a respective one of the power distribution circuits. The electric propulsion assemblies are positioned on the aircraft and operable to apply balanced forces to the aircraft such that in the event of a failure, the aircraft is not subjected to large changes in roll, pitch, and/or yaw.

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ELECTRICALLY POWERED PROPULSION SYSTEMS FOR AIRCRAFT

CROSS-REFERENCES TO OTHER APPLICATIONS

[0001] This application claims priority to U.S. provisional patent application Ser. No. 63/106,197 "VTOL AIRCRAFT FAN TILTING MECHANISMS AND ARRANGEMENTS" filed on October 27, 2020 and U.S. non-provisional Ser. No.: 17/202,855 "POWER DISTRIBUTION CIRCUITS FOR ELECTRICALLY POWERED AIRCRAFT" filed on March 16, 2021, which are hereby incorporated herein by reference in their entirety for all purposes.

FIELD

[0002] The described embodiments relate generally to electrically powered propulsion systems for aircraft. More particularly, the described embodiments relate to electrically powered aircraft propulsion systems that include power distribution circuits that provide for balanced changes in propulsion forces applied to an aircraft resulting from one or more failures within the propulsion system.

BACKGROUND

[0003] Electrically powered aircraft can includes a propulsion system that employs multiple propulsion assemblies for reliability and maneuverability. The use of multiple propulsion assemblies, however, increases the number of possible failure points and associated stability and control impacts.

SUMMARY

[0004] Electrically powered propulsion systems for aircraft are presented in which balanced distribution of electrical power among spatially distributed propulsion assemblies is used to ensure stability and control impacts that occur as a result of one or more failure conditions of the propulsion system do not induce large changes in roll, pitch, and/or yaw of the aircraft. As a result, the probability of continued safe operation of the aircraft is increased.

[0005] In one aspect, an electrically powered propulsion system for an aircraft includes batteries, electric propulsion assemblies, and power distribution circuits. Each of the power distribution circuits couples one of the batteries to two or more of the electric propulsion assemblies. The electric propulsion assemblies coupled to the battery are operable and positioned on the aircraft to apply balanced forces to the aircraft. For example, in some embodiments, the balanced forces are balanced with respect to a propulsion system balance point that is located within center of gravity (CG) limits of the aircraft. In many embodiments, the propulsion system balance point is within a relatively small distance from the center of gravity (CG) of the aircraft, the location of which can change due to variation in payload and fuel magnitudes and distributions. In many embodiments, each power distribution circuit is configured so that one or more failure conditions result in the two or more of the electric propulsion assemblies ceasing to apply the balanced forces to the aircraft, thereby ensuring a resulting balanced stability and control impact that does not induce substantial changes in roll, pitch, and/or yaw of the aircraft.

[0006] In some embodiments the two or more electric propulsion assemblies coupled with the battery include two electric propulsion assemblies that are diametrically opposed from one another with respect to a propulsion system balance point of the aircraft that is disposed within center of gravity (CG) limits of the aircraft. The propulsion system balance point can be located close to or on the center of gravity (CG) of the aircraft. In various embodiments, the electric propulsion assemblies include four electric propulsion assemblies that are operable and arranged to apply forces to the aircraft that are balanced with respect to the propulsion system balance point. In some embodiments, the electrically powered propulsion system further includes contactors (e.g., electrical relay switches). Each of the contactors can be coupled between each respective battery and each respective isolated power distribution circuit. In various embodiments, at least one of the electric propulsion assemblies includes a primary controller, a primary winding, a redundant controller, and a redundant winding. The primary controller is coupled to the primary winding. The redundant controller is coupled to the redundant winding.

[0007] In some embodiments, a first battery of the batteries is electrically coupled to a primary controller of a first propulsion assembly and a second battery of the batteries is electrically coupled to a redundant controller of the first propulsion assembly. In various embodiments, the electrically powered propulsion system further includes fuses. Each of the

fuses can couple two of the isolated power distribution circuits together such that some or all of the isolated power distribution circuits are electrically coupled together.

[0008] In another aspect, an electrically powered propulsion system for an aircraft includes a first battery, a second battery, a first electric propulsion assembly, a second electric propulsion assembly, a third electric propulsion assembly, a fourth electric propulsion assembly, a first isolated power distribution circuit, and a second isolated power distribution circuit. The first electric propulsion assembly generates a first force. The second electric propulsion assembly generates a second force. The first force and the second force can be balanced with respect to a propulsion system balance point that is located within center of gravity limits for the aircraft. The third electric propulsion assembly generates a third force. The fourth electric propulsion assembly generates a fourth force. The third force and the fourth force can be balanced with respect to the propulsion system balance point. The first isolated power distribution circuit couples the first battery to the first electric propulsion assembly and the second electric propulsion assembly. The second isolated power distribution circuit couples the second battery to the third electric propulsion assembly and the fourth electric propulsion assembly.

[0009] In some embodiments, the first electric propulsion assembly is attached to a first wing of the aircraft and the second electric propulsion assembly is attached to a second wing of the aircraft. In various embodiments, the third electric propulsion assembly is attached to the first wing of the aircraft and the fourth electric propulsion assembly is attached to the second wing of the aircraft. In some embodiments, the first isolated power distribution circuit and the second isolated power distribution circuit are primary isolated power distribution circuits. The electrically powered propulsion system can further include a first redundant power distribution circuit and a second redundant power distribution circuit. The first redundant power distribution circuit can couple the third battery to the first electric propulsion assembly and the second electric propulsion assembly. The second redundant isolated power distribution circuit can couple the fourth battery to the third electric propulsion assembly and the fourth electric propulsion assembly.

[0010] In some embodiments, the first isolated power distribution circuit is coupled to a primary controller of the first electric propulsion assembly, the second isolated power distribution circuit is coupled to a primary controller of the second electric propulsion assembly, the first redundant isolated power distribution circuit is coupled to a redundant

controller of the first electric propulsion assembly, and the second redundant isolated power distribution circuit is coupled to a redundant controller of the second electric propulsion assembly. In some embodiments, at least one of the first, second, third and fourth electric propulsion assemblies includes a primary controller, a primary winding, a redundant controller, and a redundant winding. The primary controller is coupled to the primary winding. The redundant controller is coupled to the redundant winding. In various embodiments, the electrically powered propulsion system further includes a fuse coupling the first isolated power distribution circuit to the second isolated power distribution circuit.

[0011] In another aspect, a method of powering an aircraft includes providing electrical power to first and second electric propulsion assemblies via a first isolated power distribution circuit coupled to a first battery. The first electric propulsion assembly is attached to a left wing of the aircraft and the second electric propulsion assembly is attached to a right wing of the aircraft such that the first and second electric propulsion assemblies apply respective forces that are balanced about a propulsion system balance point that is disposed within center of gravity limits for the aircraft. In various embodiments, the method of powering an aircraft further includes providing electrical power to third and fourth electric propulsion assemblies via a second isolated power distribution circuit coupled to a second battery. The third electric propulsion assembly is operable and attached to a left wing of the aircraft and the fourth electric propulsion assembly is operable and attached to a right wing of the aircraft such that the third and fourth electric propulsion assemblies apply respective forces that are balanced about the propulsion system balance point.

[0012] In some embodiments, the first and the second isolated power distribution circuits are primary isolated power distribution circuits. The method can further include: (a) providing electrical power to the first and the second electric propulsion assemblies via a first redundant isolated power distribution circuit coupled to a third battery, and (b) providing electrical power to the third and the fourth electric propulsion assemblies via a second redundant isolated power distribution circuit coupled to a fourth battery. In various embodiments, the method employs contactors (e.g., electrical relay switches). Each of the contactors can be coupled between each respective battery and each respective isolated power distribution circuit. In some embodiments, at least one of the first, second, third and fourth electric propulsion assemblies include a primary controller, a primary winding, a redundant controller, and a redundant winding. The primary controller is coupled to the primary winding. The redundant controller is coupled to a redundant winding. In various

embodiments the method further employs a fuse coupling the first isolated power distribution circuit to the second isolated power distribution circuit.

[0013] In another aspect, an aircraft includes an airframe, a first propulsion assembly, a second propulsion assembly, a third propulsion assembly, a fourth propulsion assembly, a first battery, and a second battery. The airframe has a roll axis. The first propulsion assembly is coupled with the airframe and operable to generate a first lift force applied to the airframe. The second propulsion assembly is coupled with the airframe and operable to generate a second lift force applied to the airframe. The third propulsion assembly is coupled with the airframe and operable to generate a third lift force applied to the airframe. The fourth propulsion assembly is coupled with the airframe and operable to generate a fourth lift force applied to the airframe. The first battery is connected to the first propulsion assembly to supply electric power to the first propulsion assembly to generate the first lift force and connected to the third propulsion assembly to supply electric power to the third propulsion assembly to generate the third lift force. The second battery is connected to the second propulsion assembly to supply electric power to the second propulsion assembly to generate the second lift force and connected to the fourth propulsion assembly to supply electric power to the fourth propulsion assembly to generate the fourth lift force. The first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly are spatially distributed. The first propulsion assembly and the third propulsion assembly are operable so that the first lift force and the third lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the first battery to the first propulsion assembly and to the third propulsion assembly results in substantially zero change in roll moment applied to the aircraft around the roll axis. The second propulsion assembly and the fourth propulsion assembly are operable so that the second lift force and the fourth lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the second battery to the second propulsion assembly and to the fourth propulsion assembly results in substantially zero change in roll moment applied to the aircraft around the roll axis.

[0014] The first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly can have any suitable spatial arrangement. For example, in some embodiments, the first propulsion assembly, the second propulsion

assembly, the third propulsion assembly, and the fourth propulsion assembly are spatially arranged in a rectangular array.

[0015] In some embodiments, the aircraft further includes a first battery first switch, a second battery first switch, and a control system. The first battery first switch has a closed state in which the first battery is electrically connected with the first propulsion assembly and the third propulsion assembly. The first battery first switch has an open state in which the first battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly. The second battery first switch has a closed state in which the second battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly. The second battery first switch has an open state in which the second battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly. The control system is configured to control operation of each of the first battery first switch and the second battery first switch. The control system causes the first battery first switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly. The control system causes the second battery first switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly.

[0016] In some embodiments, the aircraft further includes a first battery second switch and a second battery second switch. The first battery second switch has a closed state in which the first battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly. The first battery second switch has an open state in which the first battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly. The second battery second switch has a closed state in which the second battery is electrically connected with the first propulsion assembly and the third propulsion assembly. The second battery second switch has an open state in which the second battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly. The control system is further configured to control operation of each of the first battery second switch and the second battery second switch. The control system causes the first battery second switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly. The control system causes the second battery second switch to reconfigure from

the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly.

[0017] In some embodiments, the first, second, third, and the fourth propulsion assemblies employ primary and secondary drive current controllers and associated drive coils. For example, in some embodiments, each of the first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly include a primary drive current controller, a primary drive coil, a secondary drive current controller, and a secondary drive coil. Each of the primary drive current controllers controls supply of drive current to the associated primary drive coil. Each of the secondary drive current controllers controls supply of drive current to the associated secondary drive coil. The primary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the first battery first switch to receive electrical power from the first battery. The primary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the second battery first switch to receive electrical power from the second battery. The secondary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the second battery second switch to receive electrical power from the second battery. The secondary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the first battery second switch to receive electrical power from the first battery.

[0018] In some embodiments, the aircraft further includes a fifth propulsion assembly, a sixth propulsion assembly, a seventh propulsion assembly, an eighth propulsion assembly, a third battery, and a fourth battery. The fifth propulsion assembly is coupled with the airframe and operable to generate a fifth lift force applied to the airframe. The sixth propulsion assembly is coupled with the airframe and operable to generate a sixth lift force applied to the airframe. The seventh propulsion assembly is coupled with the airframe and operable to generate a seventh lift force applied to the airframe. The eighth propulsion assembly is coupled with the airframe and operable to generate an eighth lift force applied to the airframe. The third battery is connected to the fifth propulsion assembly to supply electric power to the fifth propulsion assembly to generate the fifth lift force and connected to the seventh propulsion assembly to supply electric power to the seventh propulsion assembly to generate the seventh lift force. The fourth battery is connected to the sixth propulsion assembly to supply electric power to the sixth propulsion assembly to generate the sixth lift force and

connected to the eighth propulsion assembly to supply electric power to the eighth propulsion assembly to generate the eighth lift force. The fifth propulsion assembly, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly are spatially distributed. The fifth propulsion assembly and the seventh propulsion assembly are operable so that the fifth lift force and the seventh lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the third battery to the fifth propulsion assembly and to the seventh propulsion assembly results in substantially zero change in roll moment applied to the aircraft around the roll axis. The sixth propulsion assembly and the eighth propulsion assembly are operable so that the sixth lift force and the eighth lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the fourth battery to the sixth propulsion assembly and to the eighth propulsion assembly results in substantially zero change in roll moment applied to the aircraft around the roll axis. In some embodiments, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly are spatially arranged in a rectangular array.

[0019] In some embodiments, the aircraft further includes a first battery first switch, a second battery first switch, a third battery first switch, a fourth battery first switch, and a control system. The first battery first switch has a closed state in which the first battery is electrically connected with the first propulsion assembly and the third propulsion assembly. The first battery first switch has an open state in which the first battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly. The second battery first switch has a closed state in which the second battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly. The second battery first switch has an open state in which the second battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly. The third battery first switch has a closed state in which the third battery is electrically connected with the fifth propulsion assembly and the seventh propulsion assembly. The third battery first switch has an open state in which the third battery is electrically disconnected from the fifth propulsion assembly and the seventh propulsion assembly. The fourth battery first switch has a closed state in which the fourth battery is electrically connected with the sixth propulsion assembly and the eighth propulsion assembly. The fourth battery first switch has an open state in which the fourth battery is electrically disconnected from the sixth propulsion

assembly and the eighth propulsion assembly. The control system is configured to control operation of each of the first battery first switch, the second battery first switch, the third battery first switch, and the fourth battery first switch. The control system causes the first battery first switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly. The control system causes the second battery first switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly. The control system causes the third battery first switch to reconfigure from the closed state to the open state in response a detected failure of the fifth propulsion assembly or the seventh propulsion assembly. The control system causes the fourth battery first switch to reconfigure from the closed state to the open state in response a detected failure of the sixth propulsion assembly or the eighth propulsion assembly.

[0020] In some embodiments, the aircraft further includes a first battery second switch, a second battery second switch, a third battery second switch, and a fourth battery second switch. The first battery second switch has a closed state in which the first battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly. The first battery second switch has an open state in which the first battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly. The second battery second switch has a closed state in which the second battery is electrically connected with the first propulsion assembly and the third propulsion assembly. The second battery second switch has an open state in which the second battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly. The third battery second switch has a closed state in which the third battery is electrically connected with the sixth propulsion assembly and the eighth propulsion assembly. The third battery second switch has an open state in which the third battery is electrically disconnected from the sixth propulsion assembly and the eighth propulsion assembly. The fourth battery second switch has a closed state in which the fourth battery is electrically connected with the fifth propulsion assembly and the seventh propulsion assembly. The fourth battery second switch has an open state in which the fourth battery is electrically disconnected from the fifth propulsion assembly and the seventh propulsion assembly. The control system is further configured to control operation of each of the first battery second switch, the second battery second switch, the third battery second switch, and the fourth battery second switch. The control system causes the first battery second switch to reconfigure from the closed state to

the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly. The control system causes the second battery second switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly. The control system causes the third battery second switch to reconfigure from the closed state to the open state in response a detected failure of the sixth propulsion assembly or the eighth propulsion assembly. The control system causes the fourth battery second switch to reconfigure from the closed state to the open state in response a detected failure of the fifth propulsion assembly or the seventh propulsion assembly.

[0021] In some embodiments of the aircraft, each of the first propulsion assembly, the second propulsion assembly, the third propulsion assembly, the fourth propulsion assembly, the fifth propulsion assembly, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly include a primary drive current controller, a primary drive coil, a secondary drive current controller, and a secondary drive coil. Each of the primary drive current controllers controls supply of drive current to the associated primary drive coil. Each of the secondary drive current controllers controls supply of drive current to the associated secondary drive coil. The primary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the first battery first switch to receive electrical power from the first battery. The primary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the second battery first switch to receive electrical power from the second battery. The primary drive current controller of each of the fifth propulsion assembly and the seventh propulsion assembly is electrically connected to the third battery first switch to receive electrical power from the third battery. The primary drive current controller of each of the sixth propulsion assembly and the eighth propulsion assembly is electrically connected to the fourth battery first switch to receive electrical power from the fourth battery. The secondary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the second battery second switch to receive electrical power from the second battery. The secondary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the first battery second switch to receive electrical power from the first battery. The secondary drive current controller of each of the fifth propulsion assembly and the seventh propulsion assembly is electrically connected to the

fourth battery second switch to receive electrical power from the fourth battery. The secondary drive current controller of each of the sixth propulsion assembly and the eighth propulsion assembly is electrically connected to the third battery second switch to receive electrical power from the third battery.

[0022] To better understand the nature and advantages of the present disclosure, reference should be made to the following description and the accompanying figures. It is to be understood, however, that each of the figures is provided for the purpose of illustration only and is not intended as a definition of the limits of the scope of the present disclosure. Also, as a general rule, and unless it is evident to the contrary from the description, where elements in different figures use identical reference numbers, the elements are generally either identical or at least similar in function or purpose.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIGS. 1A and 1B are simplified isometric views of an electrically powered aircraft in vertical (FIG. 1A) and horizontal (FIG. 1B) flight configuration according to an embodiment of the disclosure;

[0024] FIG. 2 is a simplified schematic of an electrically powered propulsion system that includes six isolated primary power distribution circuits and six isolated redundant power distribution circuits for the electronically powered aircraft shown in FIGS. 1A and 1B;

[0025] FIG. 3 is the schematic of the electrically powered propulsion system shown in FIG. 2 showing the effect of a battery failure;

[0026] FIG. 4 is the schematic of the electrically powered propulsion system shown in FIG. 2 showing the effect of a failure of a contactor or a short in the power distribution bus;

[0027] FIG. 5 is the schematic of the electrically powered propulsion system shown in FIG. 2 showing the effect of a shorted inverter or motor winding;

[0028] FIG. 6 is the schematic of the electrically powered propulsion system shown in FIG. 2 showing the effect of a seized motor;

[0029] FIG. 7 is a simplified schematic of an electrically powered propulsion system that includes six isolated primary power distribution circuits, and no redundant power distribution circuits, for the electronically powered aircraft shown in FIGS. 1A and 1B;

[0030] FIG. 8 is a simplified schematic of an electrically powered propulsion system that includes six primary power distribution circuits and six redundant power distribution circuits coupled together via fuses to form a common power bus for the electronically powered aircraft shown in FIGS. 1A and 1B; and

[0031] FIG. 9 is a simplified schematic of an electrically powered propulsion system that includes six isolated primary power distribution circuits coupled together via fuse to form a common power bus, for the electronically powered aircraft shown in FIGS. 1A and 1B.

DETAILED DESCRIPTION

[0032] Systems and techniques disclosed herein relate generally to electrically powered vertical takeoff and landing (VTOL) aircraft. More specifically, systems and techniques disclosed herein relate to electrically powered propulsion systems and methods for VTOL aircraft in which electrical power from batteries is distributed to multiple propulsion assemblies so that one or more failures in the electrically powered propulsion system does not result in an unstable change in roll, pitch, and/or yaw of the aircraft. In many embodiments, each battery supplies power via an associated power distribution circuit to a subset of propulsion assemblies of the aircraft that are operable to generate and apply counter-balancing propulsion forces so that one or more failure conditions of the propulsion system result in loss of the corresponding counter-balancing propulsion forces thereby not producing any unstable change in roll, pitch, and/or yaw of the aircraft. Various inventive embodiments are described herein, including methods, processes, systems, devices, and the like.

[0033] In order to better appreciate the features and aspects of the power distribution systems for electrically powered aircraft according to the present disclosure, further context for the disclosure is provided in the following section by discussing particular implementations of an electrically powered vertical takeoff and landing (VTOL) aircraft according to embodiments of the present disclosure. These embodiments are for example only and power distribution systems can be employed in other types of electrically powered vehicles than those depicted herein.

[0034] Several illustrative embodiments will now be described with respect to the accompanying drawings, which form a part hereof. The ensuing description provides embodiment(s) only and is not intended to limit the scope, applicability, or configuration of the disclosure. Rather, the ensuing description of the embodiment(s) will provide those

skilled in the art with an enabling description for implementing one or more embodiments. It is understood that various changes may be made in the function and arrangement of elements without departing from the spirit and scope of this disclosure. In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of certain inventive embodiments. However, it will be apparent that various embodiments may be practiced without these specific details. The figures and description are not intended to be restrictive. The word “example” or “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment or design described herein as “exemplary” or “example” is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0035] FIGS. 1A and 1B depict simplified isometric drawings of an electrically powered VTOL aircraft 100 with twelve tilting electronic propulsion assemblies 105(1) – 105(12), according to embodiments of the disclosure. More specifically, FIG. 1A depicts aircraft 100 in a vertical flight configuration and FIG. 1B depicts aircraft 100 in a horizontal flight configuration.

[0036] As shown in FIGS. 1A and 1B, in some embodiments, aircraft 100 may be configured to carry one or more passengers and/or cargo, and may be controlled automatically and/or remotely (e.g. may not require an on-board pilot to operate the aircraft). In the example shown, aircraft 100 includes a fuselage 110 that may include a cabin section for carrying passengers and/or cargo. Propulsion assemblies 105(1) – 105(12) may be mounted on opposite ends of booms 115. One or more booms 115 may be coupled to each wing 120, 125 of the aircraft 100 to enable aircraft 100 to have any number of propulsion assemblies 105. For example, each wing 120, 125 may include three booms 115, with each boom including a pair of tilting electronic propulsion assemblies 105 mounted thereon.

[0037] Aircraft 100 is illustrated in FIGS. 1A and 1B using three mutually perpendicular coordinate axes X, Y and Z, at the intersection of which is a propulsion system balance point 130 for the aircraft 100. In many embodiments, the propulsion system balance point 130 is located within center of gravity limits of the aircraft 100 and can be located within a relatively small distance from the aircraft center of gravity (CG). As known, the location of the center of gravity (CG) of an aircraft typically varies due to differences in the amount and location of payload items (e.g., fuel, passengers, cargo, etc.). The variation of the location of the center of gravity (CG) relative to the aircraft 100 during operation of the

aircraft 100 is typically constrained via applicable airworthiness regulations so that the location of the center of gravity (CG) relative to the aircraft 100 is kept within specified limits. In many embodiments, the propulsion system balance point 130 is located at a suitable location within the specified locational limits of the center of gravity (CG) so as to minimize changes in aircraft roll, pitch, and/or yaw resulting from one or more propulsion system failures as described further herein.

[0038] Aircraft 100 has six degrees of freedom including forces in each coordinate axis direction F_x , F_y , F_z and moments about each coordinate axis M_x , M_y , M_z . Aircraft 100 includes a left wing 125 opposite a right wing 120, which are both attached to fuselage 110. In this embodiment, propulsion assemblies 105 are distributed along each wing 120, 125 with an equal number on left wing 125, an equal number on right wing 120, an equal number in front of each wing, and an equal number behind each wing, thereby resulting in an equal distribution of the propulsion assemblies 105 about the propulsion system balance point 130. The equal distribution of propulsion assemblies 105 about the propulsion system balance point 130, which is located within the specified locational limits of the center of gravity (CG), combined with the power distribution approaches described herein, can be used to minimize changes in aircraft roll, pitch, and/or yaw resulting from one or more propulsion system failures as described further herein.

[0039] Aircraft 100 includes a power distribution system (not shown in FIGS. 1A and 1B) that delivers power from batteries to the propulsion assemblies 105, as described in more detail below. In many embodiments, the power distribution system includes power distribution circuits. Each of the power distribution circuits distributes power from at least one battery to at least two of the propulsion assemblies 105 that are balanced about the propulsion system balance point 130 so that if a corresponding failure condition of the propulsion system occurs, the forces applied to the aircraft from the propulsion assemblies that are discontinued as a result of the failure condition are balanced or substantially balanced about the propulsion system balance point 130, thereby resulting in a balanced reduction in the forces applied to the aircraft 100. For example, in the illustrated embodiment, propulsion assemblies 105(1) and 105(12) can be supplied power via one power distribution circuit and propulsion assemblies 105(6) and 105(7) can be supplied power via a different power distribution circuit.

[0040] If either power distribution circuit fails, for example in the configuration shown in FIG. 1A, aircraft 100 will experience a change in force along the Z axis (F_z) and resulting changes in the other forces or moments (F_x , F_y , M_x , M_y or M_z) are relatively small due to the proximity of the propulsion system balance point 130 to the aircraft center of gravity (CG) so that resulting roll, pitch, and/or yaw of the aircraft 100 is reduced as compared to conventional propulsion systems. Other examples of balanced propulsion assemblies are 2, 11; 5, 8; 3, 10; 4, 9; 1, 6, 7, 12; 2, 5, 8, 11 and 3, 4, 9, 10 in addition to others. One of ordinary skill the art will appreciate that the number and location of the electronic propulsion assemblies 105 is not limited to that illustrated in FIGS. 1A-1B and that an aircraft can include less or more propulsion assemblies, provided at other positions on the aircraft, etc.

[0041] FIG. 2 illustrates a simplified power distribution system 200 for aircraft 100 illustrated in FIGS. 1A and 1B. As shown in FIG. 2, power distribution system 200 includes twelve isolated power distribution circuits 205(1)-205(12), each coupled through a contactor 215(1)-215(12) to one of six batteries 220(1)-220(6) and arranged to supply power to two or more propulsion assemblies 105 that are balanced about the propulsion system balance point 130 (see FIGS. 1A, 1B), as described in more detail below. More specifically, in this particular embodiment there are six primary isolated power distribution circuits 205(1)-205(6) and six redundant isolated power distribution circuits 205(7)-205(12). Each power distribution circuit 205 supplies power to a balanced pair of propulsion assemblies.

[0042] For example, primary power distribution circuit 205(1) is coupled to battery 1 220(1) through contactor 215(1) and supplies power to balanced propulsion assemblies 105(1) and 105(12). As shown in FIGS. 1A and 1B, propulsion assemblies 105(1) and 105(12) are balanced about the propulsion system balance point 130 (see FIGS. 1A, 1B) because propulsion system 105(1) is the same distance along left wing 125 (e.g., +Y-axis) from the propulsion system balance point 130 that propulsion system 105(12) is along right wing 120 from the CG, providing a balanced moment M_x about the X-axis. Further, propulsion system 105(1) is a same distance forward (along +X-axis) of the propulsion system balance point 130 that propulsion system 105(12) is aft (along -X-axis) of the CG, providing a balanced moment M_y about the Y-axis. The balanced propulsion assemblies can also be called “diametrically opposed” with respect to the propulsion system balance point 130.

[0043] In this particular embodiment, each propulsion system 105 includes a primary controller 225(1)-225(12) coupled to a primary winding 230(1)-230(12) and a redundant controller 235(1)-235(12) coupled to a redundant winding 240(1)-240(12). Primary winding 230(1)-230(12) and redundant winding 240(1)-240(12) each couple power to a respective shaft 245(1)-245(12) that rotates a respective propeller 250(1)-250(12). Primary controller 225 and primary winding 230 are electrically isolated from redundant controller 235 and redundant winding 240 such that if one controller or winding fails, shaft 245 still receives $\frac{1}{2}$ power from the other controller and winding.

[0044] For example, propulsion system 105(1) can receive $\frac{1}{2}$ power from battery 220(1) through primary power distribution circuit 205(1) that is coupled to primary controller 225(1) and primary winding 230(1) and receives $\frac{1}{2}$ power from battery 220(6) through redundant power distribution circuit 205(12) that is coupled to redundant controller 235(1) and redundant winding 240(1). Thus, if battery 220(1) fails, propulsion system 105(1) can still receive $\frac{1}{2}$ power from battery 6 220(6). Since propulsion assemblies 105(1) and 105(12) are balanced, the power to each propulsion system can be the same. In some embodiments, a control or computing system 255 is used and can compensate and boost power supplied from battery 6 220(6) to propulsion assemblies 105(1) and 105(12) to compensate for the loss of $\frac{1}{2}$ power due to a failure of battery 1 220(1).

[0045] In a like manner, battery 2 220(2) supplies power to propulsion assemblies 105(2) and 105(11) through primary power distribution circuit 205(2); battery 3 220(3) supplies power to propulsion assemblies 105(3) and 105(10) through primary power distribution circuit 205(3); battery 4 220(4) supplies power to propulsion assemblies 105(4) and 105(9) through primary power distribution circuit 205(4), battery 5 220(5) supplies power to propulsion assemblies 105(5) and 105(8) through primary power distribution circuit 205(5) and battery 6 220(6) supplies power to propulsion assemblies 105(6) and 105(7) through primary power distribution circuit 205(6).

[0046] In this embodiment there are also six redundant power distribution circuits 205(7)-205(12). Battery 1 220(1) supplies power to propulsion assemblies 105(6) and 105(7) through redundant power distribution circuit 205(7); battery 2 220(2) supplies power to propulsion assemblies 105(5) and 105(8) through redundant power distribution circuit 205(8); battery 3 220(3) supplies power to propulsion assemblies 105(4) and 105(9) through redundant power distribution circuit 205(9); battery 4 220(4) supplies power to propulsion

assemblies 105(3) and 105(10) through redundant power distribution circuit 205(10); battery 5 220(5) supplies power to propulsion assemblies 105(2) and 105(11) through redundant power distribution circuit 205(5); battery 6 220(6) supplies power to propulsion assemblies 105(1) and 105(12) through redundant power distribution circuit 205(6). As appreciated by one of skill having the benefit of this disclosure other arrangements of primary and redundant power distribution circuits and propulsion assemblies are within the scope of this disclosure.

[0047] As shown in FIG. 2, each primary and redundant power distribution circuit 205 is coupled to a respective battery 220 via a respective contactor 215(1)-215(12). That is, each contactor 215 controls power supplied to a balanced pair of propulsion assemblies 105 via a respective power distribution circuit 205. In some embodiments each contactor 215 is an electromechanical relay while in other embodiments it can be a different device, including but not limited to one or more solid-state switches. In various embodiments contactor 215 can be controlled with a current sensing circuit that senses a current flowing into or out of the respective battery 220. When the current reaches a predetermined threshold, contactor 215 can open, breaking the connection between the battery 220 and the respective power distribution circuit 205. Each power distribution circuit 205 shown in FIG. 2 by a single line is representative of a DC circuit that includes at least a power and a ground conductor. In some embodiments a common ground conductor can be used for two or more power distribution circuits 205. In various embodiments contactors 215 can be positioned between only the positive or the ground conductor and battery 220 while in other embodiments they can be positioned between both the power and the ground conductors. In further embodiments fuses can be used in place of contactors 215 or in addition to contactors.

[0048] In some embodiments control system 255 can be coupled to controllers 225, 235, contactors 215 and/or batteries 220 to control one or more functions of power distribution system 200, as described in more detail below. In one embodiment, control system 255 can make adjustments in one or more controllers 225, 235 to maintain batteries 220 at a similar charge state. More specifically, in some embodiments one or more batteries 220 may be aged (e.g., older or having experienced more discharge cycles) and have a reduced charge capacity and/or one or more batteries may be swapped for a freshly charged battery such that batteries have an unequal charge state. Control system 255 can receive information from each battery 220 related to its charge state and adjust power drawn from each battery by adjusting an operation of one or more controllers 225, 235.

[0049] In some embodiments, each controller 225, 235 includes an inverter that receives DC power from power distribution circuit 205 and converts it to AC power that is supplied to motor windings 230, 240 in terms of torque, rpm, blade pitch angle, etc. In various embodiments each propulsion system 105 includes an AC motor, however in other embodiments it can include multiple motors coupled to a single shaft and in further embodiments can be a DC motor. In some embodiments, such as shown in FIGS. 1A and 1B, aircraft 100 is over-actuated, that is it has more propulsion assemblies 105 (e.g., 12) than degrees of freedom (e.g., 6) and therefore control system 255 can adjust myriad combinations of controllers 225, 235 to discharge a particular battery 220 faster or slower than others to maintain an equal charge state among all of the batteries. Thus, control system 255 can use forces and moments (e.g., F_x , F_y , F_z , M_x , M_y , M_z) and charge state of batteries 220 as inputs and can output commands to controllers 225, 235 to optimize charge state, and power usage.

[0050] In some embodiments, the balanced arrangement of the propulsion assemblies 105 on aircraft 100 enables even discharge of batteries 220 during cross-winds and other conditions. For example, as shown in FIG. 1A a cross-wind approaching from the left (e.g., from propulsion assemblies 105(1), 105(7) towards propulsion assemblies 105(6), 105(12) causes power draw from propulsion assemblies 105(1) and 105(7) to reduce and power draw from propulsion assemblies 105(6) and 105(12) to increase. However, as shown in FIG. 2, propulsion assemblies 105(1) and 105(12) are coupled to the same batteries (e.g., batteries 220(1) and 220(6)) thus the increased power draw of 105(12) offsets the decreased power draw of 105(1), thus batteries 220(1) and 220(6) maintain a relatively similar rate of discharge as batteries 220(2)-220(5). Similarly, propulsion assemblies 105(6) and 105(7) are balanced.

[0051] In some embodiments one or more diodes can be coupled in-series with power distribution circuits such that current can only flow out of batteries and not into batteries to protect the power distribution system in case of a shorted battery. In other embodiments power distribution system enables regenerative charging in which propulsion assemblies generate energy (e.g., during descent) and transfer power to batteries.

[0052] FIGS. 3-6 illustrate the operation of power distribution system 200 in the event of example failure modes. Other failure modes and responses to failure modes by power distribution system, although not shown, are within the scope of this disclosure. FIG. 3 illustrates the power distribution system 200 shown in FIG. 2, however in FIG. 3 battery

220(1) is shown as failed. As shown in FIG. 3, failed battery 220(1) causes contactor 215(1) and contactor 215(7) to open such that power is no longer supplied to propulsion system 105(1) via primary controller 225(1), to propulsion system 105(12) via primary controller 225(12) to propulsion system 105(6) via redundant controller 235(6) and to propulsion system 105(7) via redundant controller 235(7). Thus, propulsion assemblies 105(1), 105(6), 105(7) and 105(12) can receive $\frac{1}{2}$ the power that they were receiving before battery 220(1) failure.

[0053] As described above, in some embodiments control system 255 can detect the failure, open contactors 215(1), 215(7) and immediately increase power to propulsion assemblies 105(1), 105(6), 105(7) and 105(12) from battery 220(6) to restore 100% power to the aircraft. Alternatively, because of the balanced nature of the power distribution circuits 205, control system 255 can increase power to propulsion assemblies 105(1) and 105(12) to compensate for the entire power loss from battery 220(1), or could alternatively increase power to propulsion assemblies 105(6) and 105(7). Alternatively, control system 255 could take more complex action and increase power from battery 220(2) to propulsion assemblies 105(2) and 105(11), for example, to compensate for the failure. One of skill in the art having the benefit of this disclosure will appreciate the many different options controller can use to compensate for the loss of battery 220(1).

[0054] FIG. 4 illustrates power distribution system 200 shown in FIG. 2, however in FIG. 4 battery contactor 215(1) has failed and/or there is a short within power distribution circuit 205(1). As shown in FIG. 3, contactor 215(1) can be opened once the failure is detected which cuts off power from power distribution circuit 205(1) which supplies power to balanced propulsion assemblies 105(1) and 105(12). Thus power is reduced to aircraft 100 in a balanced matter. Because contactor 215(1) breaks the connection between the failure and battery 220(1), the battery can still supply power to power distribution circuit 205(7) and propulsion assemblies 105(6) and 105(7) via contactor 215(7).

[0055] FIG. 5 illustrates power distribution system 200 shown in FIG. 2, however in FIG. 5 primary controller 225(1) and/or primary winding 230(1) has failed. As shown in FIG. 5, contactor 215(1) can be opened once the failure is detected which cuts off power from power distribution circuit 205(1) and from battery 220(1) to primary controller 225(1) and primary winding 230(1). Propulsion system 105(1) can still receive $\frac{1}{2}$ power from battery 220(6) via redundant power distribution circuit 205(12).

[0056] FIG. 6 illustrates power distribution system 200 shown in FIG. 2, however in FIG. 6 shaft 245(1) of first propulsion system 105(1) is seized. As shown in FIG. 6, contactor 215(1) can be opened once the failure is detected which cuts off power from power distribution circuit 205(1) and from battery 220(1). Similarly, contactor 215(12) can be opened which cuts off power from redundant power distribution circuit 205(12) and from battery 220(6). Because of the balanced arrangement, opening contactors 215(1), 215(12) also results in a complete loss of power delivered to propulsion system 105(12). Because the loss of power to propulsion assemblies 105(1) and 105(12) is balanced, aircraft 100 will not rotate in response to the failure and will only lose altitude or speed. Control system 255 can compensate for the failure in myriad ways, as described above.

[0057] FIG. 7 illustrates a power distribution system 700 that is similar to power distribution system 200 shown in FIG. 2, however in FIG. 7 the redundant power distribution circuits 205(7)-205(12) have been removed. As shown in FIG. 7 each propulsion system 705(1)-705(12) has only a primary controller 225 and a primary winding 230. The primary power distribution circuits 205(1)-205(6) still supply power to propulsion assemblies 105 in a balanced manner. However, if a primary power distribution circuit 205(1)-205(6) fails there is no redundant power distribution circuit to continue to supply power to propulsion assemblies 705. For example, if battery 220(1) fails, contactor 215(1) opens and balanced propulsion assemblies 705(1) and 705(12) cease operation. Control system 255 can compensate by increasing power from battery 220(6) to balanced propulsion assemblies 705(6) and 705(7) or by taking myriad other actions.

[0058] FIG. 8 illustrates a power distribution system 800 that is similar to power distribution system 200 shown in FIG. 2, however in FIG. 8 each primary power distribution circuit 205(1)-205(6) and each redundant power distribution circuit 205(7)-205(12) has been coupled together with a fuse 805(1)-805(10). As shown in FIG. 8 first fuse 805(1) couples first and second primary power distribution circuits, 205(1), 205(2), respectively, second fuse 805(2) couples second and third primary power distribution circuits 205(2), 205(3), respectively, and similar connections are made for third fuse through fifth fuse, 805(3) – 805(5), respectively. Similarly, redundant power distribution circuits 205(7)-205(12) are coupled together with sixth fuse 805(6) that couples first and second redundant power distribution circuits 205(7), 205(8), respectively, seventh fuse 805(7) that couples second and third redundant power distribution circuits 205(8), 205(9), respectively, and similar connections are made for eighth fuse through tenth fuse, 805(8) – 805(10), respectively.

[0059] Fuses 805 result in all power distribution circuits 205 having a common voltage level as they are all electrically coupled together. This arrangement enables the even discharge of batteries 220 and power sharing along the common bus. In the event of a shorted battery failure, e.g., battery 220(2), first fuse 805(1), second fuse 805(2), sixth fuse 805(6) and seventh fuse 805(7) blow, isolating first battery 220(1) from batteries 220(3)-220(6). Essentially, a failure causes the failed power distribution circuits to “island” as a result of the fuses on either side of the failure blowing. In some embodiments contactors can be included, as shown in FIG. 2 to decouple each battery from primary and/or redundant power distribution circuits.

[0060] FIG. 9 illustrates a power distribution system 900 that is similar to power distribution system 800 shown in FIG. 8 and power distribution system 200 shown in FIG. 2, however in FIG. 9 the redundant power distribution circuits 205(7)-205(12) have been removed. As shown in FIG. 9 each propulsion system 905 has only a primary controller 225 and a primary winding 230. Primary power distribution circuits 205(1)-205(6) are each coupled together via fuses 805(1)-805(5) to form a common bus and supply power to propulsion assemblies 905 in a balanced matter. Fuses 805 result in all power distribution circuits 205 having a common voltage level as they are all electrically coupled together. This arrangement enables the even discharge of batteries 220 and power sharing along the common bus. Similar to FIG. 8, in the event of a failure, the failed power distribution circuits and/or battery is “islanded” through the blowing of one or more fuses on either side of the failure. In some embodiments contactors can be included, as shown in FIG. 2 to decouple each battery from primary and/or redundant power distribution circuits.

[0061] Although aircraft 100 (see FIG. 1) is described and illustrated as one particular configuration of aircraft, embodiments of the disclosure are suitable for use with a multiplicity of aircraft. For example, any aircraft that uses two or more electronic propulsion assemblies can be used with embodiments of the disclosure. In some instances, embodiments of the disclosure are particularly well suited for use with aircraft that carry one or more persons because of the need for reliability, however the power distribution system disclosed herein is not limited to “manned” aircraft and can be used on any aircraft “manned” and “unmanned” of any size.

[0062] For simplicity, various electrical components, such as capacitors, current sense circuits, controller details, processors communications busses, memory, storage devices and other components of the power distribution system are not shown in the figures.

[0063] In the foregoing specification, embodiments of the disclosure have been described with reference to numerous specific details that can vary from implementation to implementation. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. The sole and exclusive indicator of the scope of the disclosure, and what is intended by the applicants to be the scope of the disclosure, is the literal and equivalent scope of the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction. The specific details of particular embodiments can be combined in any suitable manner without departing from the spirit and scope of embodiments of the disclosure.

[0064] Additionally, spatially relative terms, such as "bottom" or "top" and the like can be used to describe an element and/or feature's relationship to another element(s) and/or feature(s) as, for example, illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use and/or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as a "bottom" surface can then be oriented "above" other elements or features. The device can be otherwise oriented (e.g., rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0065] With reference to the appended figures, components that can include memory (e.g., control or computing system 255, controllers 225, 235, etc.) can include non-transitory machine-readable media. The terms "machine-readable medium" and "computer-readable medium" as used herein refer to any storage medium that participates in providing data that causes a machine to operate in a specific fashion. In embodiments provided hereinabove, various machine-readable media might be involved in providing instructions/code to processors and/or other device(s) for execution. Additionally or alternatively, the machine-readable media might be used to store and/or carry such instructions/code. In many implementations, a computer-readable medium is a physical and/or tangible storage medium. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Common forms of computer-readable media

include, for example, magnetic and/or optical media, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code.

[0066] The methods, systems, and devices discussed herein are examples. Various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. The various components of the figures provided herein can be embodied in hardware and/or software. Also, technology evolves and, thus, many of the elements are examples that do not limit the scope of the disclosure to those specific examples.

[0067] It has proven convenient at times, principally for reasons of common usage, to refer to such signals as bits, information, values, elements, symbols, characters, variables, terms, numbers, numerals, or the like. It should be understood, however, that all of these or similar terms are to be associated with appropriate physical quantities and are merely convenient labels. Unless specifically stated otherwise, as is apparent from the discussion above, it is appreciated that throughout this specification discussions utilizing terms such as “processing,” “computing,” “calculating,” “determining,” “ascertaining,” “identifying,” “associating,” “measuring,” “performing,” or the like refer to actions or processes of a specific apparatus, such as a special purpose computer, controller, or a similar special purpose electronic computing device. In the context of this specification, therefore, a special purpose computer or a similar special purpose electronic computing device is capable of manipulating or transforming signals, typically represented as physical electronic, electrical, or magnetic quantities within memories, registers, or other information storage devices, transmission devices, or display devices of the special purpose computer or similar special purpose electronic computing device.

[0068] Those of skill in the art will appreciate that information and signals used to communicate the messages described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above

description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0069] Terms “and,” “or,” and “an/or,” as used herein, may include a variety of meanings that also is expected to depend at least in part upon the context in which such terms are used. Typically, “or” if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the term “one or more” as used herein may be used to describe any feature, structure, or characteristic in the singular or may be used to describe some combination of features, structures, or characteristics. However, it should be noted that this is merely an illustrative example and claimed subject matter is not limited to this example. Furthermore, the term “at least one of” if used to associate a list, such as A, B, or C, can be interpreted to mean any combination of A, B, and/or C, such as A, B, C, AB, AC, BC, AA, AAB, ABC, AABBBCCC, etc.

[0070] Reference throughout this specification to “one example,” “an example,” “certain examples,” or “exemplary implementation” means that a particular feature, structure, or characteristic described in connection with the feature and/or example may be included in at least one feature and/or example of claimed subject matter. Thus, the appearances of the phrase “in one example,” “an example,” “in certain examples,” “in certain implementations,” or other like phrases in various places throughout this specification are not necessarily all referring to the same feature, example, and/or limitation. Furthermore, the particular features, structures, or characteristics may be combined in one or more examples and/or features.

[0071] In the preceding detailed description, numerous specific details have been set forth to provide a thorough understanding of claimed subject matter. However, it will be understood by those skilled in the art that claimed subject matter may be practiced without these specific details. In other instances, methods and apparatuses that would be known by one of ordinary skill have not been described in detail so as not to obscure claimed subject matter. Therefore, it is intended that claimed subject matter not be limited to the particular examples disclosed, but that such claimed subject matter may also include all aspects falling within the scope of appended claims, and equivalents thereof.

[0072] For an implementation involving firmware and/or software, the methodologies may be implemented with modules (e.g., procedures, functions, and so on) that perform the

functions described herein. Any machine-readable medium tangibly embodying instructions may be used in implementing the methodologies described herein. For example, software codes may be stored in a memory and executed by a processor unit. Memory may be implemented within the processor unit or external to the processor unit. As used herein the term “memory” refers to any type of long term, short term, volatile, nonvolatile, or other memory and is not to be limited to any particular type of memory or number of memories, or type of media upon which memory is stored.

[0073] If implemented in firmware and/or software, the functions may be stored as one or more instructions or code on a computer-readable storage medium. Examples include computer-readable media encoded with a data structure and computer-readable media encoded with a computer program. Computer-readable media includes physical computer storage media. A storage medium may be any available medium that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, compact disc read-only memory (CD-ROM) or other optical disk storage, magnetic disk storage, semiconductor storage, or other storage devices, or any other medium that can be used to store desired program code in the form of instructions or data structures and that can be accessed by a computer; disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

[0074] In addition to storage on computer-readable storage medium, instructions and/or data may be provided as signals on transmission media included in a communication apparatus. For example, a communication apparatus may include a transceiver having signals indicative of instructions and data. The instructions and data are configured to cause one or more processors to implement the functions outlined in the claims. That is, the communication apparatus includes transmission media with signals indicative of information to perform disclosed functions. At a first time, the transmission media included in the communication apparatus may include a first portion of the information to perform the disclosed functions, while at a second time the transmission media included in the communication apparatus may include a second portion of the information to perform the disclosed functions.

What is claimed is:

1. An electrically powered propulsion system for an aircraft, the electrically powered propulsion system comprising:
a plurality of batteries;
a plurality of electric propulsion assemblies; and
a plurality of isolated power distribution circuits, each coupling a battery of the plurality of batteries to two or more electric propulsion assemblies of the plurality of electric propulsion assemblies, the two or more electric propulsion assemblies positioned on the aircraft to apply balanced forces to the aircraft.
2. The electrically powered propulsion system of claim 1 wherein the balanced forces applied to the aircraft are balanced with respect to a propulsion system balance point that is located within center of gravity (CG) limits of the aircraft.
3. The electrically powered propulsion system of claim 1 wherein the two or more electric propulsion assemblies include two electric propulsion assemblies that are diametrically opposed from one another with respect to a propulsion system balance point that is located within center of gravity (CG) limits of the aircraft.
4. The electrically powered propulsion system of claim 1 wherein the two or more electric propulsion assemblies include four electric propulsion assemblies that are arranged to apply forces to the aircraft that are balanced with respect to a propulsion system balance point that is located within center of gravity (CG) limits of the aircraft.
5. The electrically powered propulsion system of claim 1 further comprising a plurality of contactors, each contactor coupled between each respective battery and each respective isolated power distribution circuit.
6. The electrically powered propulsion system of claim 1 wherein at least one electric propulsion system of the plurality of electric propulsion assemblies includes a primary controller coupled to a primary winding and a redundant controller coupled to a redundant winding.

7. The electrically powered propulsion system of claim 1 wherein a first battery of the plurality of batteries is electrically coupled to a primary controller of a first propulsion system and wherein a second battery of the plurality of batteries is electrically coupled to a redundant controller of the first propulsion system.
8. The electrically powered propulsion system of claim 1 further comprising a plurality of fuses, each fuse coupling two isolated power distribution circuits of the plurality of isolated power distribution circuits together such that the plurality of isolated power distribution circuits are electrically coupled together.
9. An electrically powered propulsion system for an aircraft, the electrically powered propulsion system comprising:
 - a first and a second battery;
 - a first electric propulsion assembly that generates a first force and a second electric propulsion assembly that generates a second force, wherein the first and the second forces are balanced with respect to a center of gravity of the aircraft;
 - a third electric propulsion assembly that generates a third force and a fourth electric propulsion assembly that generates a fourth force, wherein the third and the fourth forces are balanced with respect to the center of gravity of the aircraft;
 - a first isolated power distribution circuit coupling the first battery to the first and the second electric propulsion assemblies; and
 - a second isolated power distribution circuit coupling the second battery to the third and the fourth electric propulsion assemblies.
10. The electrically powered propulsion system of claim 9 wherein the first electric propulsion assembly is attached to a first wing of the aircraft and the second electric propulsion assembly is attached to a second wing of the aircraft.
11. The electrically powered propulsion system of claim 10 wherein the third electric propulsion assembly is attached to the first wing of the aircraft and the fourth electric propulsion assembly is attached to the second wing of the aircraft.
12. The electrically powered propulsion system of claim 9 wherein the first and the second isolated power distribution circuits are primary isolated power distribution circuits, the power distribution circuit further comprising:

a first redundant isolated power distribution circuit coupling a third battery to the first and the second electric propulsion assemblies; and
a second redundant isolated power distribution circuit coupling a fourth battery to the third and the fourth electric propulsion assemblies.

13. The electrically powered propulsion system of claim 12 wherein:
the first and the second isolated power distribution circuits are coupled to a primary controller of the first electric propulsion assembly and to a primary controller of the second electric propulsion assembly, respectively; and
the first and the second redundant isolated power distribution circuits are coupled to a redundant controller of the first electric propulsion assembly and to a redundant controller of the second electric propulsion assembly, respectively.
14. The electrically powered propulsion system of claim 9 wherein at least one electric propulsion assembly of the first, second, third and fourth electric propulsion assemblies includes a primary controller coupled to a primary winding and a redundant controller coupled to a redundant winding.
15. The electrically powered propulsion system of claim 9 further comprising a fuse coupling the first isolated power distribution circuit to the second isolated power distribution circuit.
16. A method of powering an aircraft comprising:
providing electrical power to first and second electric propulsion assemblies via a first isolated power distribution circuit coupled to a first battery, wherein the first electric propulsion assembly is attached to a left wing of the aircraft and the second electric propulsion assembly is attached to a right wing of the aircraft, and wherein the first and second electric propulsion assemblies are operable to apply respective lift forces that are balanced about a centerline of the aircraft; and
providing electrical power to third and fourth electric propulsion assemblies via a second isolated power distribution circuit coupled to a second battery, wherein the third electric propulsion assembly is attached to a left wing of the aircraft and the fourth electric propulsion assembly is attached to a right wing of the aircraft, and wherein the third and fourth electric propulsion assemblies are

operable to apply respective lift forces that are balanced about the centerline of the aircraft.

17. The method of claim 16 wherein the first and the second isolated power distribution circuits are primary isolated power distribution circuits, the method further comprising:
providing electrical power to the first and the second electric propulsion assemblies via a first redundant isolated power distribution circuit coupled to a third battery; and
providing electrical power to the third and the fourth electric propulsion assemblies via a second redundant isolated power distribution circuit coupled to a fourth battery.
18. The method of claim 16 further comprising contactors, wherein each contactor is coupled between one of the first and second batteries and one of the first and second isolated power distribution circuits.
19. The method of claim 16 wherein at least one of the first, second, third, and fourth electric propulsion assemblies includes a primary controller coupled to a primary winding and a redundant controller coupled to a redundant winding.
20. The method of claim 16 further comprising a fuse coupling the first isolated power distribution circuit to the second isolated power distribution circuit.
21. An aircraft comprising:
an airframe having a roll axis;
a first propulsion assembly coupled with the airframe and operable to generate a first lift force applied to the airframe;
a second propulsion assembly coupled with the airframe and operable to generate a second lift force applied to the airframe;
a third propulsion assembly coupled with the airframe and operable to generate a third lift force applied to the airframe;
a fourth propulsion assembly coupled with the airframe and operable to generate a fourth lift force applied to the airframe;
a first battery connected to the first propulsion assembly to supply electric power to the first propulsion assembly to generate the first lift force and connected to

the third propulsion assembly to supply electric power to the third propulsion assembly to generate the third lift force; and

a second battery connected to the second propulsion assembly to supply electric power to the second propulsion assembly to generate the second lift force and connected to the fourth propulsion assembly to supply electric power to the fourth propulsion assembly to generate the fourth lift force,

wherein first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly are spatially distributed,

wherein the first propulsion assembly and the third propulsion assembly are operable so that the first lift force and the third lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the first battery to the first propulsion assembly and to the third propulsion assembly results in substantially zero roll moment applied to the aircraft around the roll axis, and

wherein the second propulsion assembly and the fourth propulsion assembly are operable so that the second lift force and the fourth lift force are equal in magnitude and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the second battery to the second propulsion assembly and to the fourth propulsion assembly results in substantially zero roll moment applied to the aircraft around the roll axis.

22. The aircraft of claim 21, wherein the first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly are spatially arranged in a rectangular array.

23. The aircraft of claim 21, further comprising:
- a first battery first switch having a closed state in which the first battery is electrically connected with the first propulsion assembly and the third propulsion assembly and an open state in which the first battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly;
 - a second battery first switch having a closed state in which the second battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly and an open state in which the second battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly; and
 - a control system configured to control operation of each of the first battery first switch and the second battery first switch, wherein the control system causes the first battery first switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly, and wherein the control system causes the second battery first switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly.
24. The aircraft of claim 23, further comprising:
- a first battery second switch having a closed state in which the first battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly and an open state in which the first battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly; and
 - a second battery second switch having a closed state in which the second battery is electrically connected with the first propulsion assembly and the third propulsion assembly and an open state in which the second battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly,
- wherein the control system is further configured to control operation of each of the first battery second switch and the second battery second switch,

wherein the control system causes the first battery second switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly, and

wherein the control system causes the second battery second switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly.

25. The aircraft of claim 24, wherein:

each of the first propulsion assembly, the second propulsion assembly, the third propulsion assembly, and the fourth propulsion assembly comprise a primary drive current controller, a primary drive coil, a secondary drive current controller, and a secondary drive coil, wherein each of the primary drive current controllers controls supply of drive current to the associated primary drive coil, and wherein each of the secondary drive current controllers controls supply of drive current to the associated secondary drive coil;

the primary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the first battery first switch to receive electrical power from the first battery;

the primary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the second battery first switch to receive electrical power from the second battery;

the secondary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the second battery second switch to receive electrical power from the second battery; and

the secondary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the first battery second switch to receive electrical power from the first battery.

26. The aircraft of claim 21, further comprising:

a fifth propulsion assembly coupled with the airframe and operable to generate a fifth lift force applied to the airframe;

a sixth propulsion assembly coupled with the airframe and operable to generate a sixth lift force applied to the airframe;

a seventh propulsion assembly coupled with the airframe and operable to generate a seventh lift force applied to the airframe;

an eighth propulsion assembly coupled with the airframe and operable to generate an eighth lift force applied to the airframe;

a third battery connected to the fifth propulsion assembly to supply electric power to the fifth propulsion assembly to generate the fifth lift force and connected to the seventh propulsion assembly to supply electric power to the seventh propulsion assembly to generate the seventh lift force; and

a fourth battery connected to the sixth propulsion assembly to supply electric power to the sixth propulsion assembly to generate the sixth lift force and connected to the eighth propulsion assembly to supply electric power to the eighth propulsion assembly to generate the eighth lift force,

wherein fifth propulsion assembly, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly are spatially distributed,

wherein the fifth propulsion assembly and the seventh propulsion assembly are operable so that the fifth lift force and the seventh lift force are equal in magnitude, and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the third battery to the fifth propulsion assembly and to the seventh propulsion assembly results in substantially zero roll moment applied to the aircraft around the roll axis, and

wherein the sixth propulsion assembly and the eighth propulsion assembly are operable so that the sixth lift force and the eighth lift force are equal in magnitude, and combine to generate substantially zero roll moment applied to the aircraft around the roll axis so that loss of supply of electrical power from the fourth battery to the sixth propulsion assembly and to the eighth propulsion assembly results in substantially zero roll moment applied to the aircraft around the roll axis.

27. The aircraft of claim 26, wherein the fifth propulsion assembly, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly are spatially arranged in a rectangular array.

28. The aircraft of claim 26, further comprising:
- a first battery first switch having a closed state in which the first battery is electrically connected with the first propulsion assembly and the third propulsion assembly and an open state in which the first battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly;
 - a second battery first switch having a closed state in which the second battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly and an open state in which the second battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly;
 - a third battery first switch having a closed state in which the third battery is electrically connected with the fifth propulsion assembly and the seventh propulsion assembly and an open state in which the third battery is electrically disconnected from the fifth propulsion assembly and the seventh propulsion assembly;
 - a fourth battery first switch having a closed state in which the fourth battery is electrically connected with the sixth propulsion assembly and the eighth propulsion assembly and an open state in which the fourth battery is electrically disconnected from the sixth propulsion assembly and the eighth propulsion assembly; and
 - a control system configured to control operation of each of the first battery first switch, the second battery first switch, the third battery first switch, and the fourth battery first switch,
- wherein the control system causes the first battery first switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly,
- wherein the control system causes the second battery first switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly,
- wherein the control system causes the third battery first switch to reconfigure from the closed state to the open state in response a detected failure of the fifth propulsion assembly or the seventh propulsion assembly, and

wherein the control system causes the fourth battery first switch to reconfigure from the closed state to the open state in response a detected failure of the sixth propulsion assembly or the eighth propulsion assembly.

29. The aircraft of claim 28, further comprising:

a first battery second switch having a closed state in which the first battery is electrically connected with the second propulsion assembly and the fourth propulsion assembly and an open state in which the first battery is electrically disconnected from the second propulsion assembly and the fourth propulsion assembly;

a second battery second switch having a closed state in which the second battery is electrically connected with the first propulsion assembly and the third propulsion assembly and an open state in which the second battery is electrically disconnected from the first propulsion assembly and the third propulsion assembly;

a third battery second switch having a closed state in which the third battery is electrically connected with the sixth propulsion assembly and the eighth propulsion assembly and an open state in which the third battery is electrically disconnected from the sixth propulsion assembly and the eighth propulsion assembly; and

a fourth battery second switch having a closed state in which the fourth battery is electrically connected with the fifth propulsion assembly and the seventh propulsion assembly and an open state in which the fourth battery is electrically disconnected from the fifth propulsion assembly and the seventh propulsion assembly,

wherein the control system is further configured to control operation of each of the first battery second switch, the second battery second switch, the third battery second switch, and the fourth battery second switch,

wherein the control system causes the first battery second switch to reconfigure from the closed state to the open state in response a detected failure of the second propulsion assembly or the fourth propulsion assembly,

wherein the control system causes the second battery second switch to reconfigure from the closed state to the open state in response a detected failure of the first propulsion assembly or the third propulsion assembly,

wherein the control system causes the third battery second switch to reconfigure from the closed state to the open state in response a detected failure of the sixth propulsion assembly or the eighth propulsion assembly, and
wherein the control system causes the fourth battery second switch to reconfigure from the closed state to the open state in response a detected failure of the fifth propulsion assembly or the seventh propulsion assembly.

30. The aircraft of claim 29, wherein:

each of the first propulsion assembly, the second propulsion assembly, the third propulsion assembly, the fourth propulsion assembly, the fifth propulsion assembly, the sixth propulsion assembly, the seventh propulsion assembly, and the eighth propulsion assembly comprise a primary drive current controller, a primary drive coil, a secondary drive current controller, and a secondary drive coil, wherein each of the primary drive current controllers controls supply of drive current to the associated primary drive coil, and wherein each of the secondary drive current controllers controls supply of drive current to the associated secondary drive coil;

the primary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the first battery first switch to receive electrical power from the first battery;

the primary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the second battery first switch to receive electrical power from the second battery;

the primary drive current controller of each of the fifth propulsion assembly and the seventh propulsion assembly is electrically connected to the third battery first switch to receive electrical power from the third battery;

the primary drive current controller of each of the sixth propulsion assembly and the eighth propulsion assembly is electrically connected to the fourth battery first switch to receive electrical power from the fourth battery;

the secondary drive current controller of each of the first propulsion assembly and the third propulsion assembly is electrically connected to the second battery second switch to receive electrical power from the second battery;

the secondary drive current controller of each of the second propulsion assembly and the fourth propulsion assembly is electrically connected to the first battery second switch to receive electrical power from the first battery;

the secondary drive current controller of each of the fifth propulsion assembly and the seventh propulsion assembly is electrically connected to the fourth battery second switch to receive electrical power from the fourth battery; and

the secondary drive current controller of each of the sixth propulsion assembly and the eighth propulsion assembly is electrically connected to the third battery second switch to receive electrical power from the third battery.

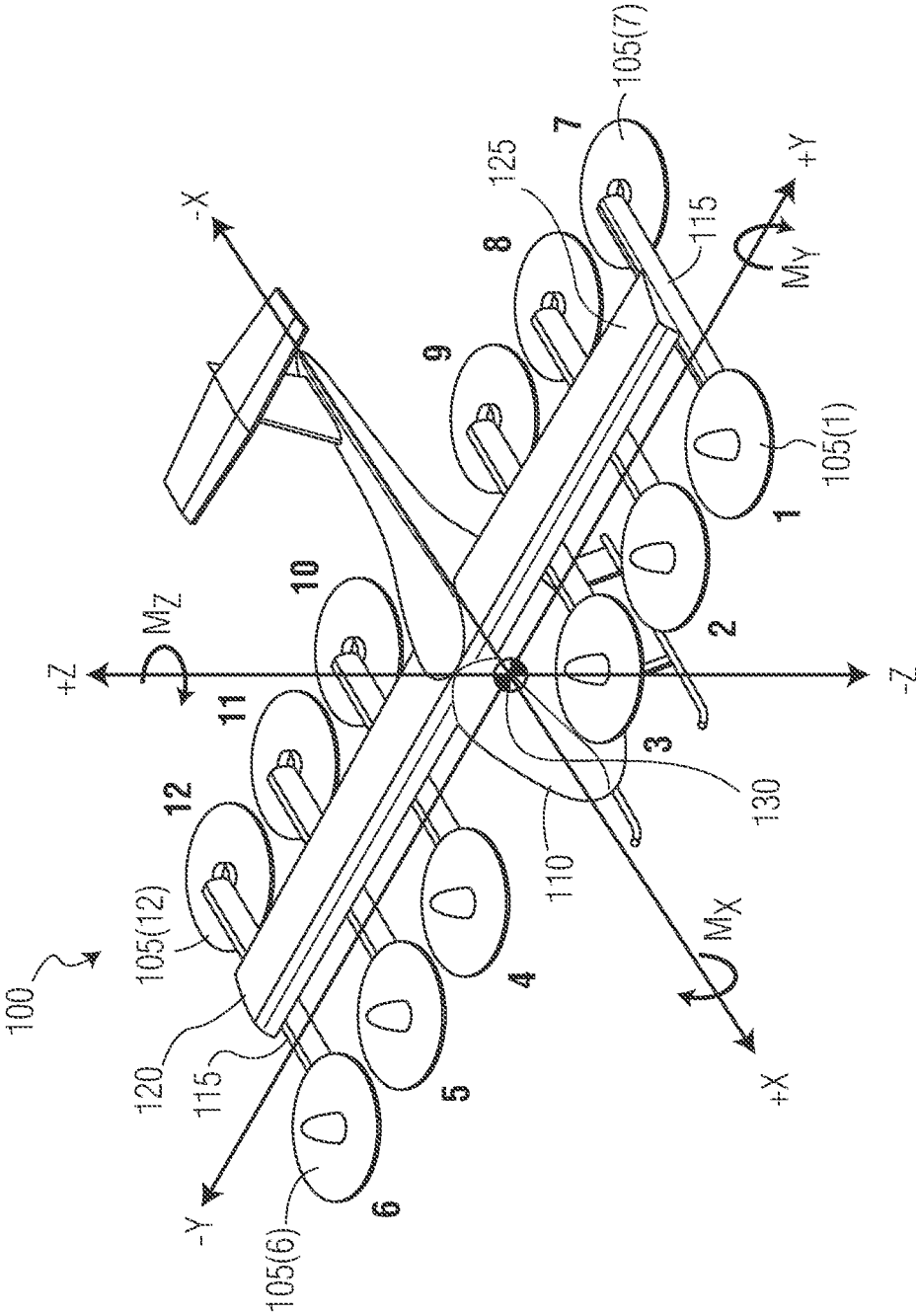


FIG. 1A

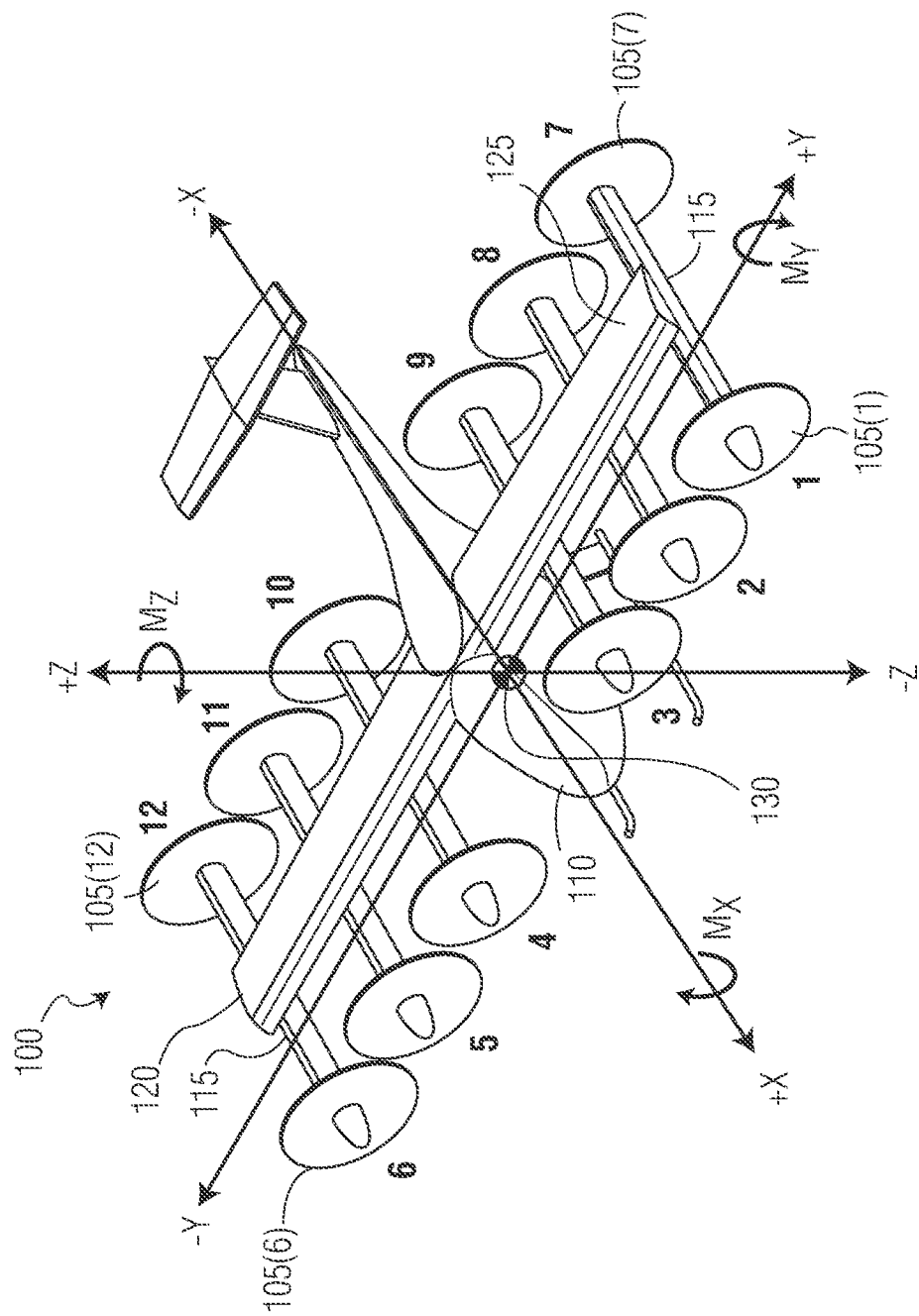


FIG. 1B

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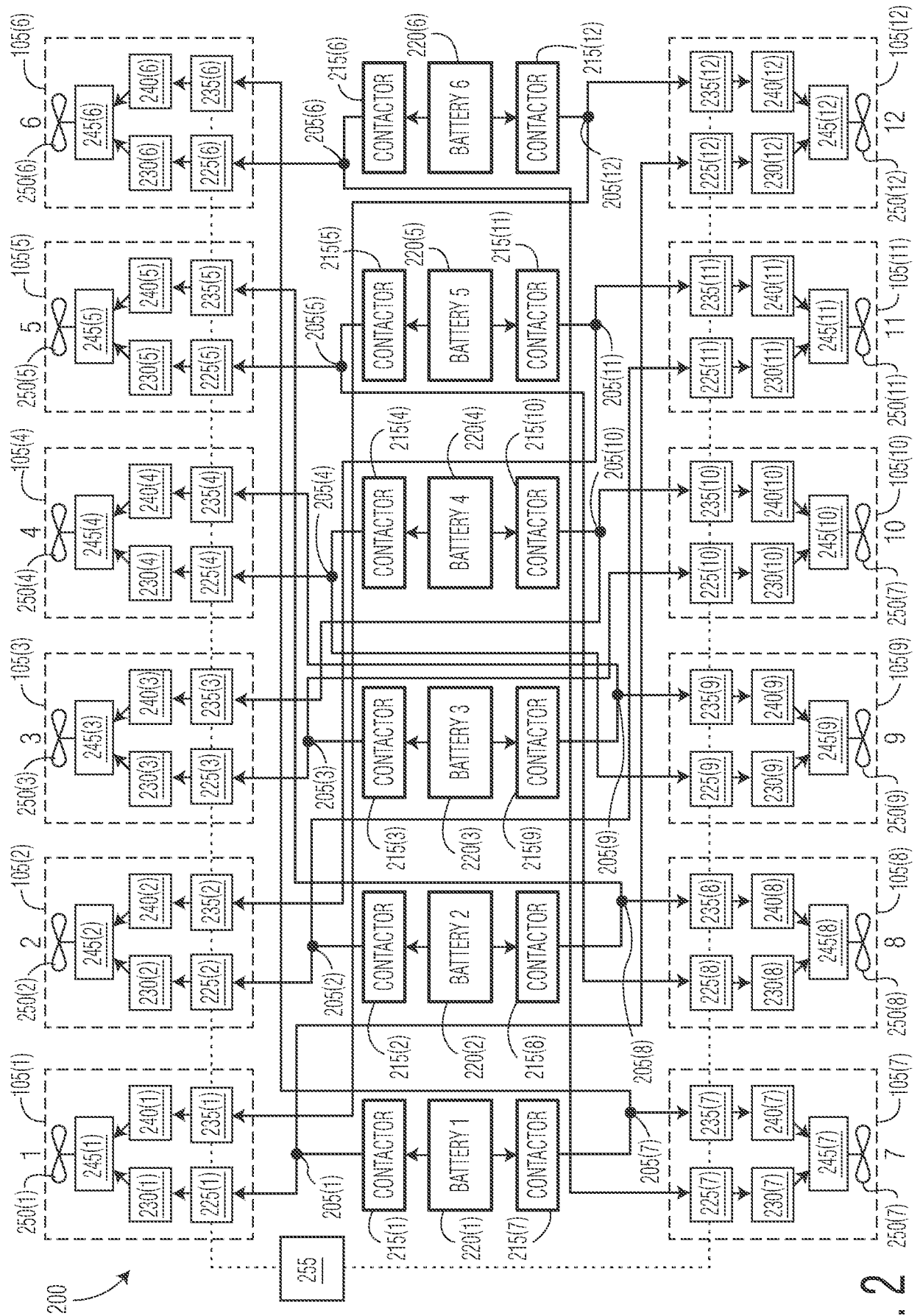


FIG. 2

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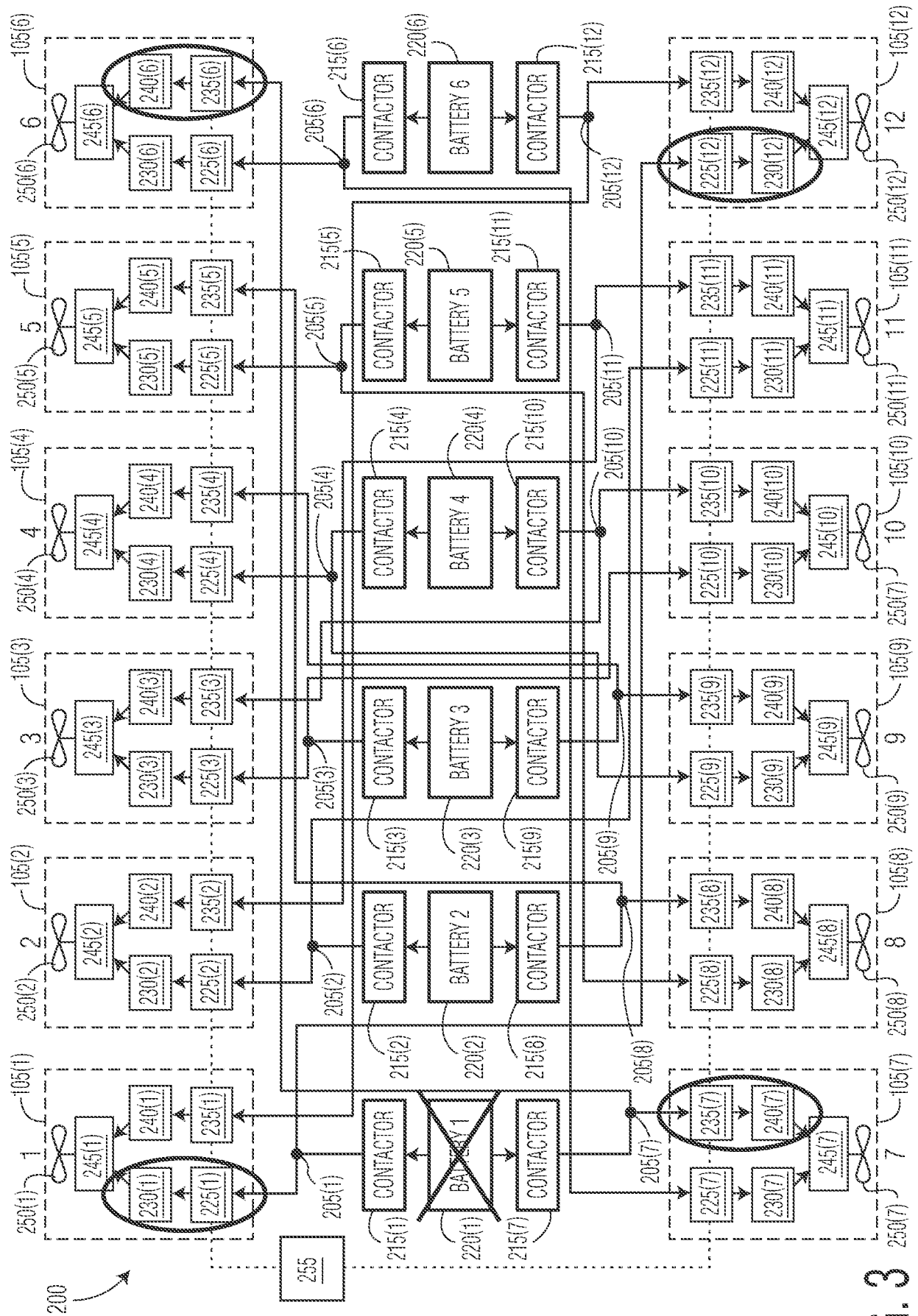


FIG. 3

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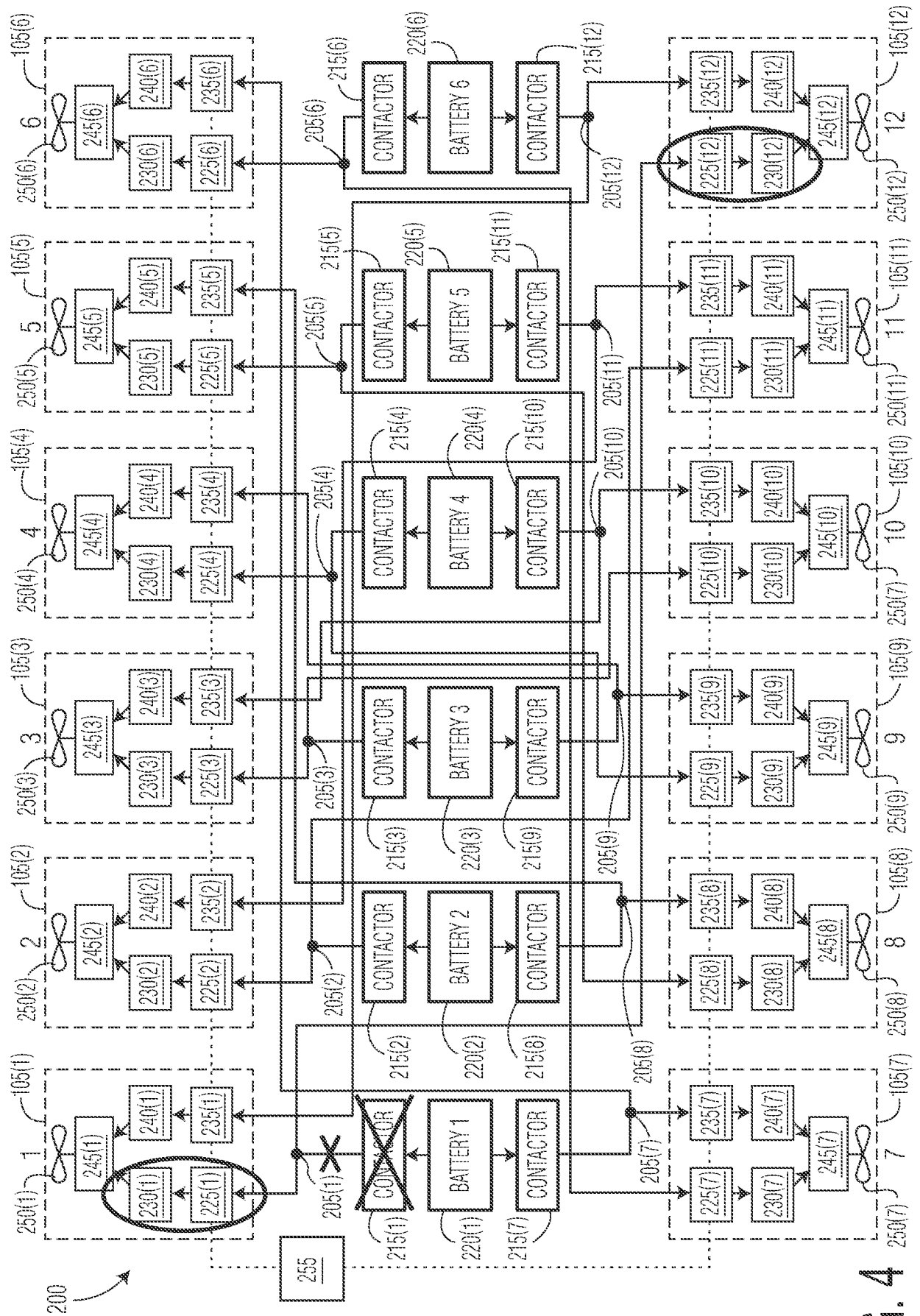
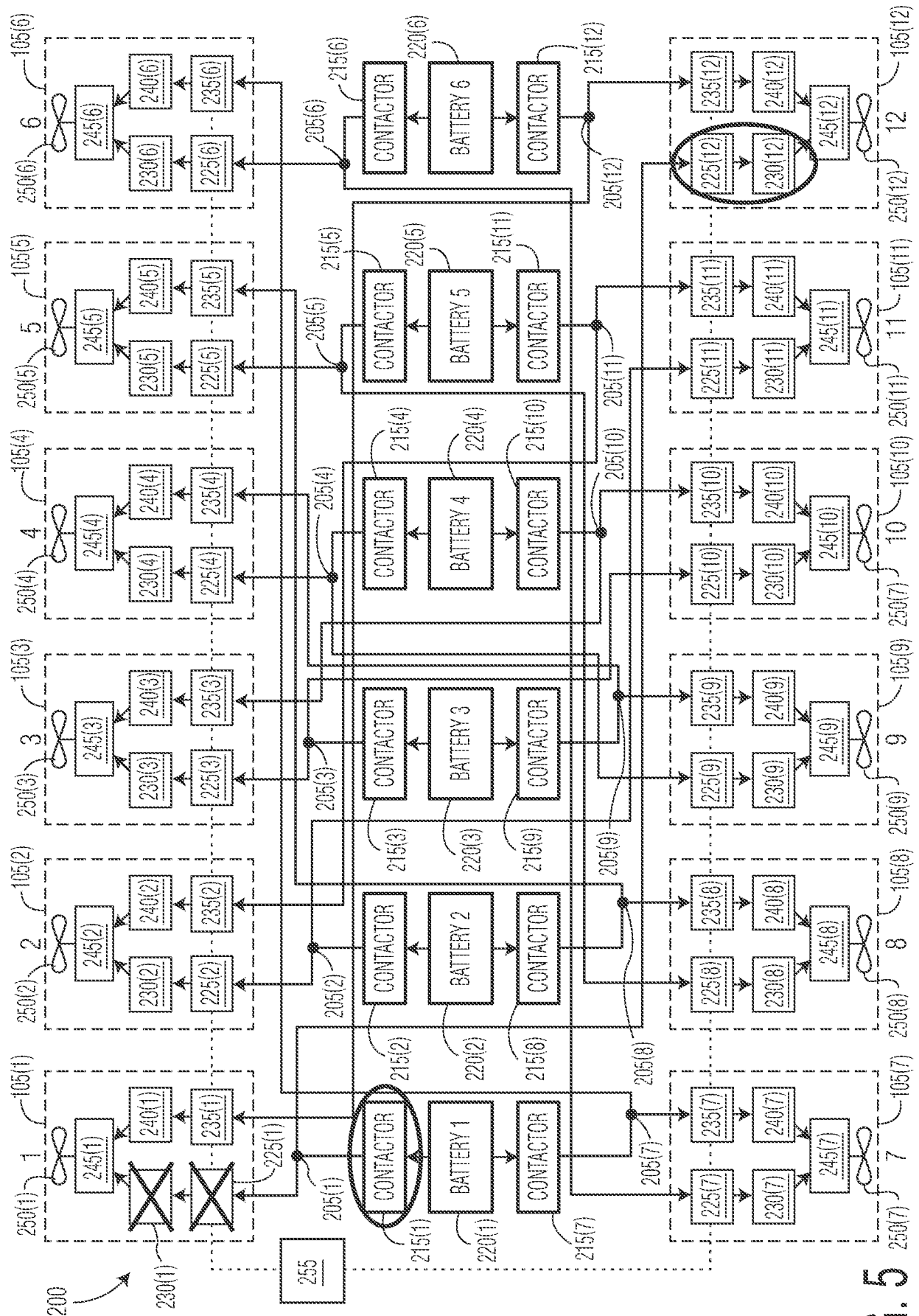


FIG. 4



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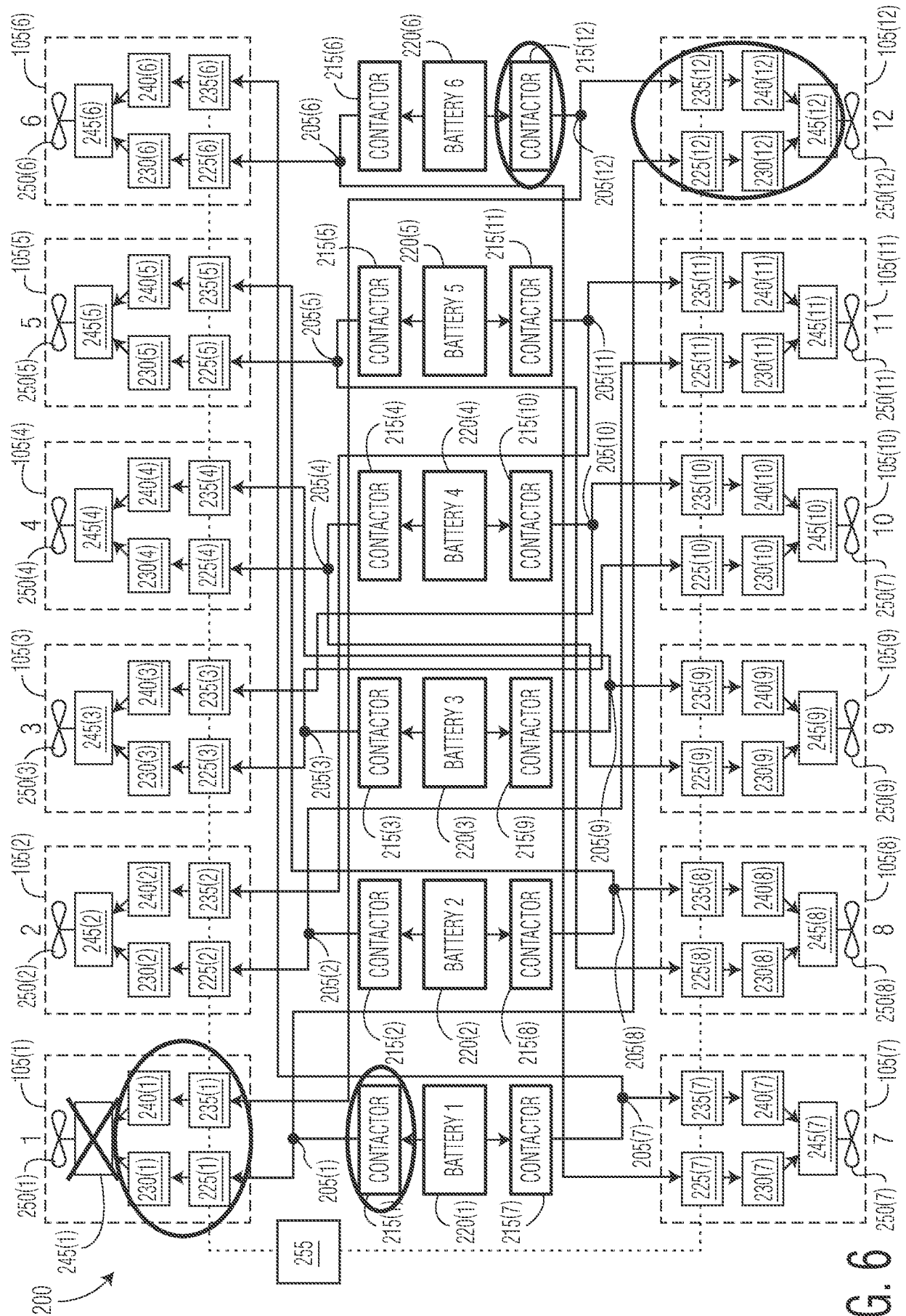


FIG. 6

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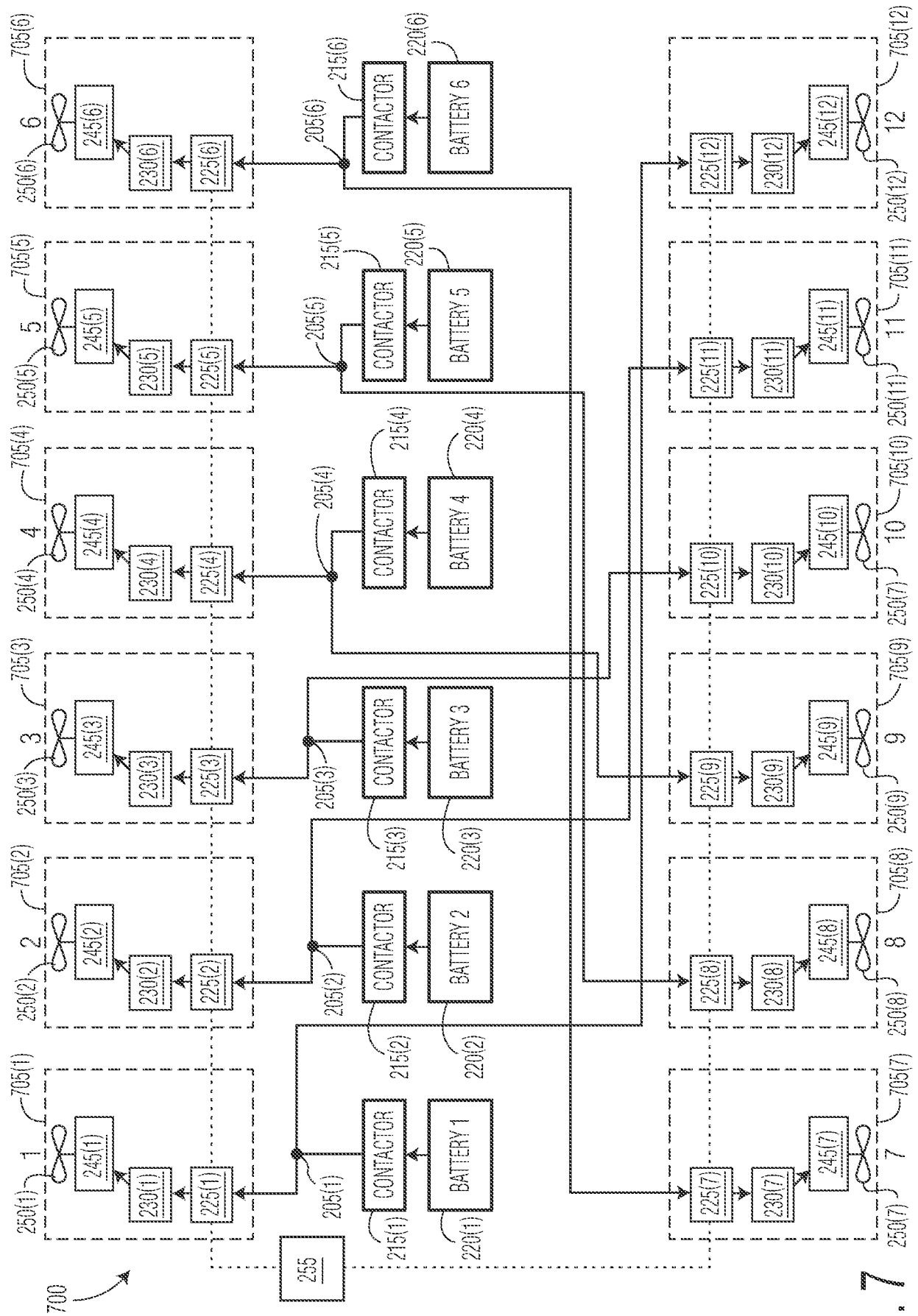


FIG. 7

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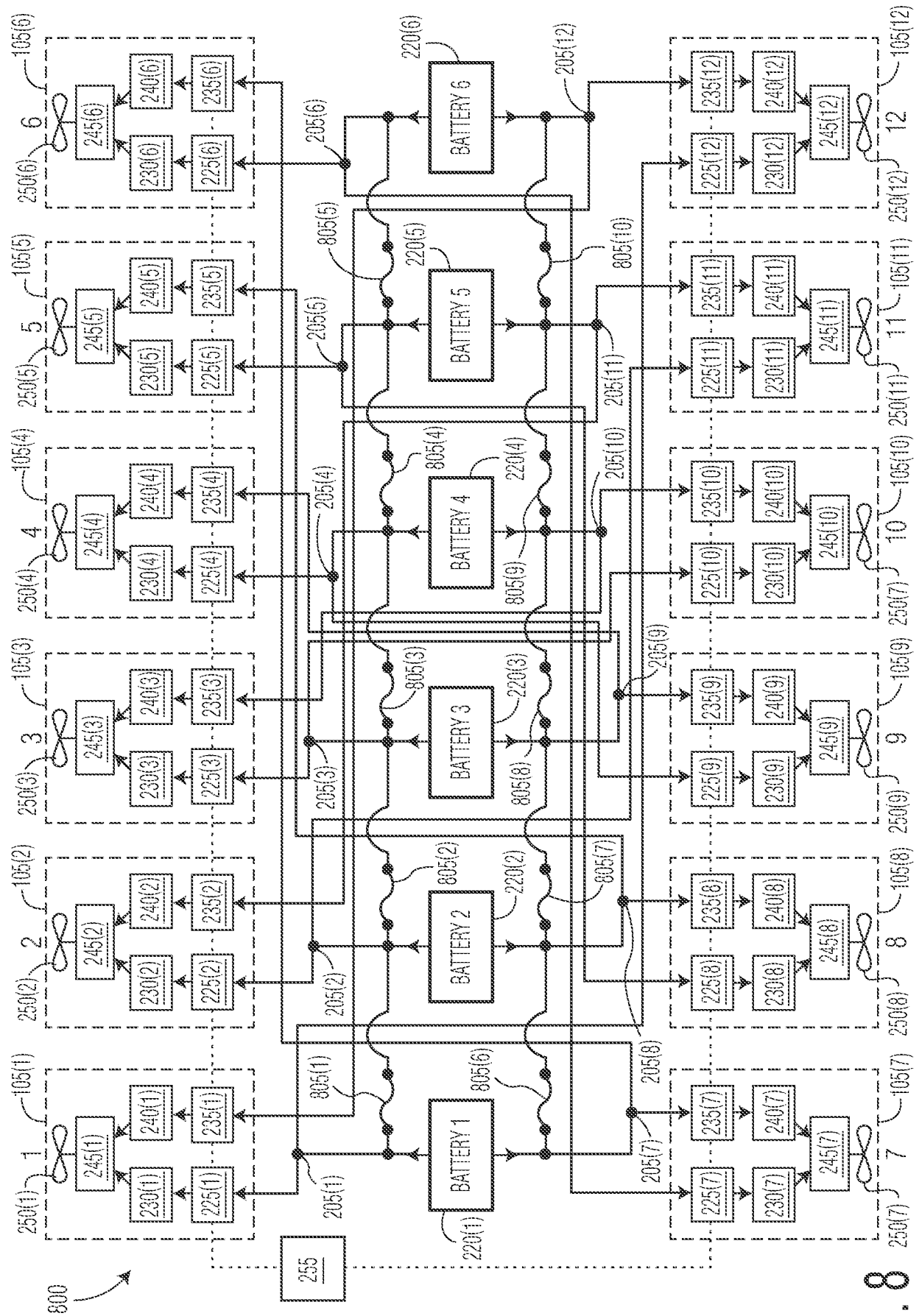


FIG. 8

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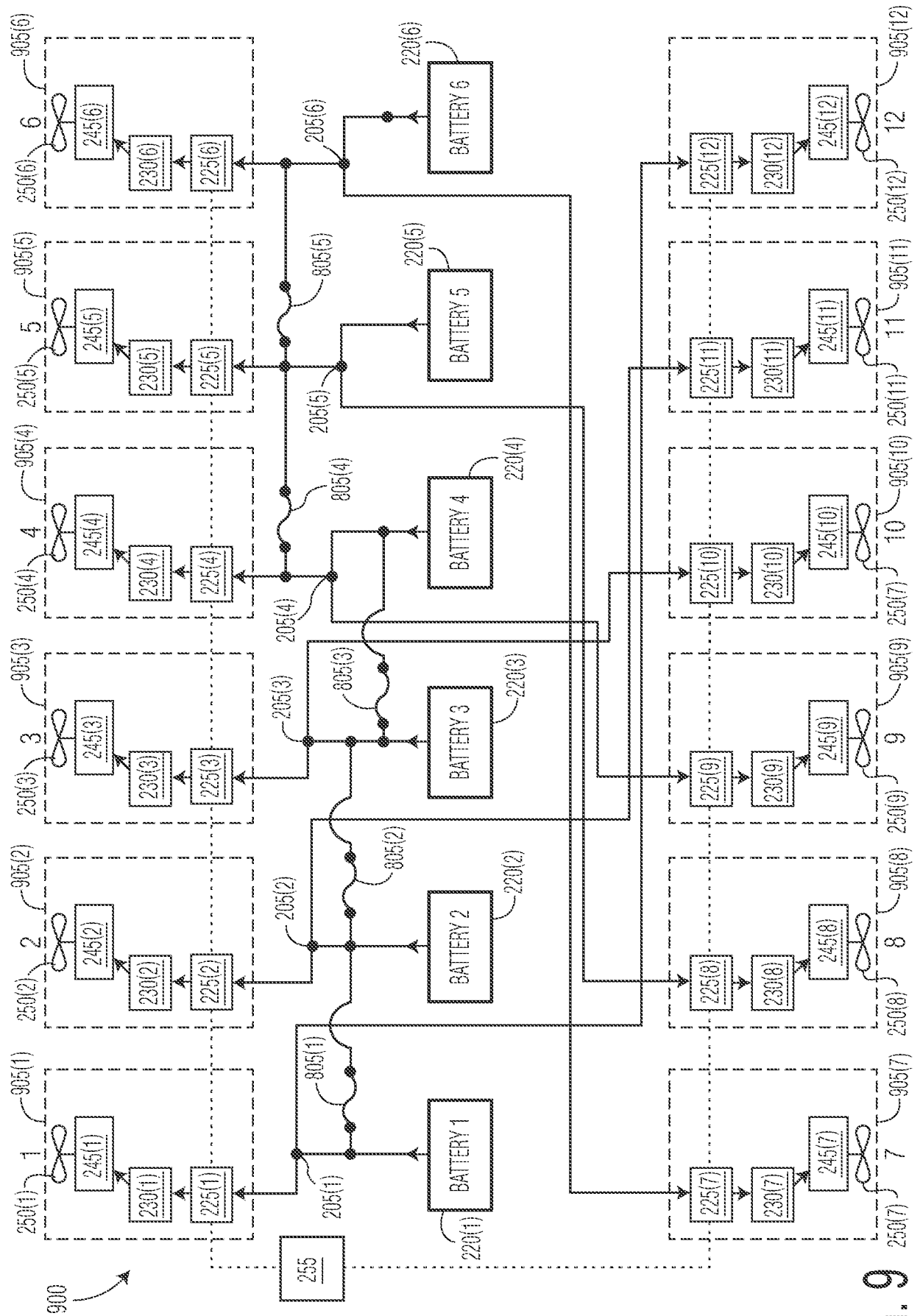


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2021/056667

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B64D 27/24; B64C 29/00; B64C 39/02; B64C 39/08; B64D 41/00 (2021.01)

CPC - B64D 27/24; B64C 29/0025; H02J 4/00 (2021.08)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2018/0312248 A1 (SKYKAR INC.) 01 November 2018 (01.11.2018) entire document	1-7, 16-19 --- 8-15, 20
Y	US 2008/0197961 A1 (PATEL) 21 August 2008 (21.08.2008) entire document	8, 15, 20
Y	US 6,415,242 B1 (WELDON, JR. et al) 02 July 2002 (02.07.2002) entire document	9-15
Y	US 2004/0042145 A1 (GARNETT) 04 March 2004 (04.03.2004) entire document	13

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

26 December 2021

Date of mailing of the international search report

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